



Full length article

Long-term residential magnetic field exposure and neurodegenerative disease mortality: An 18-year nationwide cohort study in Switzerland

Nekane Sandoval-Diez ^{a,b}, Nicolas Loizeau ^{a,b}, Anke Huss ^c, Martin Röösli ^{a,b},
Danielle Vienneau ^{a,b,d,*}

^a Department of Epidemiology and Public Health, Swiss Tropical and Public Health Institute, Kreuzstrasse 2, 4123 Allschwil, Switzerland

^b University of Basel, Petersplatz 1, 4003 Basel, Switzerland

^c Institute for Risk Assessment Sciences, Utrecht University, 3584 Utrecht, the Netherlands

^d Julius Centre for Health Sciences and Primary Care, University Medical Center Utrecht 3584 Utrecht, the Netherlands

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ABSTRACT

Background: Epidemiological evidence on the association between extremely low-frequency magnetic fields (ELF-MF) exposure and neurodegenerative diseases (NDD) remains inconsistent. Few population-based studies using exposure from high-voltage power lines (HVPL) have found mixed findings, and none have yet considered exposure from railway lines.

Methods: We followed 3,555,064 adults from the Swiss National Cohort (2001–2018), contributing 55.4 million person-years. Long-term ELF-MF exposure from HVPL (50 Hz) and railway lines (16.7 Hz) was modelled using validated proximity models and updated over four intervals (2001–2005, 2006–2010, 2011–2015, 2016–2018). Long-term ELF-MF exposure was calculated as a time-weighted average exposure over 10-year windows preceding each interval. Cox proportional hazards models estimated hazard ratios (HRs) for mortality from Alzheimer's disease (AD), other types of dementia (OTD), amyotrophic lateral sclerosis (ALS), Parkinson's disease (PD), and multiple sclerosis (MS), adjusting for sociodemographic and environmental co-exposures.

Results: During follow-up, 146,655 NDD deaths occurred. Less than 1% of the population was exposed to long-term ELF-MF $\geq 0.3 \mu\text{T}$ from HVPL and 2.4% from railway lines. HVPL exposure was positively associated with mortality from AD (HR per $1 \mu\text{T}$ increase in exposure = 1.54; 95% CI: 1.23–1.92) and OTD (HR = 1.31; 95% CI: 1.13–1.52). Associations for railway exposure were weaker and attenuated after adjusting for environmental co-exposures. No associations were observed for ALS, PD, or MS.

Conclusions: Long-term ELF-MF exposure was associated with higher dementia mortality risk in the general population, but not with ALS, PD, or MS. Causal inference remains limited by the absence of established biological mechanisms.

1. Background

The widespread use of electricity has resulted in sustained human exposure to extremely low-frequency magnetic fields (ELF-MF). At the residential level, exposure is closely related to the network of generation and distribution of alternating current (AC) for electric power supply and transport network systems, as well the utilization of domestic electrical installations (Gajšek et al., 2016; Bonato et al., 2023). In Europe, population exposure to ELF-MF is generally low, average levels typically between 0.01 and 0.2 μT (Gajšek et al., 2016; Bonato et al., 2023). A recent nationwide monitoring study in Switzerland reported

median ELF-MF levels between 0.03 and 0.20 μT (Loizeau et al., 2024). However, around 0.5% of the general public experiences long-term ELF-MF levels above 0.2 μT , mainly due to proximity of their homes to high-voltage power lines (HVPL) or railway overhead lines (Gajšek et al., 2016).

The potential health risks associated with ELF-MF exposure remains a topic of debate. In 2001, the International Agency for Research on Cancer (IARC) classified ELF-MF as a potential human carcinogen (Group 2B), based on “inadequate evidence” from animal studies and “limited” epidemiologic evidence linking exposure above 0.3–0.4 μT to childhood leukaemia (IARC Working Group on the Evaluation of

* Corresponding author at: Department of Epidemiology and Public Health, Swiss Tropical and Public Health Institute, Kreuzstrasse 2, 4123 Allschwil, Switzerland.
E-mail addresses: danielle.vienneau@swisstph.ch, D.M.Vienneau@umcutrecht.nl (D. Vienneau).

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Carcinogenic Risks to Humans, 2002). Beyond cancer outcomes, ELF-MF exposure has been suggested as a risk factor for neurodegenerative diseases (NDD). The first study to investigate this association (Sobel et al., 1995) reported a threefold increase in Alzheimer's disease (AD) risk among workers with high occupational ELF-MF exposure, which motivated subsequent research in occupational settings. Recently, the SCHEER (Scientific Committee on Health, Environmental and Emerging Risks) (2024) concluded that there is weak evidence of an association between occupational exposure to ELF-MF and AD and dementia, moderate evidence of an association with amyotrophic lateral sclerosis (ALS), and no evidence of an association with Parkinson's disease (PD) or multiple sclerosis (MS). For residential exposure, the Committee found the evidence on the risk of these neurodegenerative diseases to be uncertain.

Among the few studies on ELF-MF exposure in residential settings, Huss et al. (2009) observed an increased risk of AD mortality among people with long residential history near HVPL in Switzerland. Subsequent studies in Denmark (Frei et al., 2013) and Italy (Gervasi et al., 2019) provided weak indications of increased AD, and consistently null findings for ALS, PD, and MS. Importantly, residential ELF-MF exposure from railway lines, a potentially relevant source for everyday ELF-MF exposure, has not yet been investigated.

Building directly on the work by Huss et al. (2009), we used the Swiss National Cohort (SNC) with an extended follow-up of 18 years. Compared to this previous study, we refined the exposure assessment by applying validated proximity models and, for the first time, considering residential exposure from railway lines. We examined the association between long-term residential ELF-MF exposure from high-voltage power lines and railway lines and mortality from AD, other types of dementia (OTD), ALS, PD, and MS in the adult population in Switzerland, providing one of the most comprehensive assessments to date of residential ELF-MF exposure and NDD risk in the general population.

2. Methods

2.1. Study population

This study used data from the Swiss National Cohort (SNC), with ethical approval by the Ethics Commission of Northwest and Central Switzerland (EKNZ). The SNC is a longitudinal research platform based on the Swiss decennial national censuses of 1990 and 2000, which transitioned to annual registry-based census in 2010 (Bopp et al., 2009; Spoerri et al., 2010). The 1990 and 2000 censuses were linked to each other and to birth, death, and emigration records using a combination of deterministic and probabilistic linkage methods. Participation was mandatory, ensuring that nearly all residents in Switzerland were included at the time of the census, e.g. 95% in the 2000 census (Renaud, 2004). Since 2010, the registry-based cohort exclusively uses deterministic linkage for these records. The 1990 and 2000 censuses were both conducted on 4 December; for this study, we shifted the start of these to 1 January 1991 and 2001, respectively, to align with the start of the newer, annual registry-based census.

The SNC provides basic demographic data, a Swiss socioeconomic position index (Swiss-SEP) (Panczak et al., 2023), and geo-coded residential locations at each census year (1991, 2001, and annually from 2010). Mortality data is coded according to the 10th edition of the International Classification of Diseases (ICD-10). The SNC does not include information on individual lifestyle factors, medical or family history.

Using the SNC database, we established a closed cohort with an 18-year follow-up period from 1 January 2001 to 31 December 2018. We included individuals aged 30 years or older at baseline (1 January 2001) to define an adult population appropriate for the heterogeneous age-at-onset distributions of the NDD outcomes considered. In addition, individuals needed to be present in both the 1991 and 2001 censuses to enable long-term residential exposure estimation (see Section 2.3).

Individuals were censored at death, emigration, or the end of follow-up. The analysis was based on 3 555 064 individuals, after excluding 187 290 observations (4.6% of the original sample) due to a mismatch between the former probabilistic and current deterministic SNC linkage; 4 770 (0.1%) due to shifting the baseline date to allow follow-up starting on 1 January 2001; 85 005 (2.1%) with missing residential coordinates in 1991 and 2001 census; 90 710 (2.2%) residing in hotels, hospitals, or long-term care facilities, and assigned a community centroid geocode; 40 752 (1.0%) with missing sociodemographic covariates at baseline (education level and Swiss-SEP, see Section 2.4); and 155 997 (3.8%) with missing environmental co-exposures (transportation noise and residential greenness, see Section 2.4) throughout the follow-up (see Table S1).

2.2. Outcomes

The primary outcome was mortality from neurodegenerative diseases when reported as the primary, concomitant, consecutive, or initial cause of death on the death certificate: Alzheimer's disease (ICD-10: G30), other types of dementia (ICD-10: F01 [vascular dementia] and F03 [unspecified dementia]), amyotrophic lateral sclerosis (ICD-10: G12.2), Parkinson's disease (ICD-10: G20), and multiple sclerosis (ICD-10: G35). ICD-10 code F02 ("dementia in other diseases classified elsewhere") was not included in the definition of other types of dementia, as it represents dementia secondary to specific underlying conditions rather than a primary dementia diagnosis.

2.3. Exposure assessment

We estimated residential ELF-MF exposure from HVPL and railway lines using proximity models. The horizontal distance to the nearest HVPL or railway line was calculated and used as input for the models. In the absence of detailed line characteristics, the use of a simple proximity model was justified by the strong inverse relationship between magnetic field strength and distance from the line (Kaune & Zaffanella, 1991). Moreover, distance was demonstrated to be a robust proxy for long-term ELF-MF exposure at the group level (Amoon et al., 2020).

Spatial data for HVPL (operating at 50 Hz) were sourced from the Swiss Terrain Landscape Model in 3D (O'Sullivan et al., 2008; Swisstopo, 2023), and complemented with the Electricity Transmission Lines Sector Plan dataset (Bundesamt für Energie BFE, 2023). The resulting high-voltage electricity grid comprised 7214.8 km (4566.9 km from HVPL of 220–380 kV, 2647.9 km from HVPL of 36–150 kV). Spatial data for railway lines (16.7 Hz) was obtained from the Federal Office of Transport Railway Network dataset (Federal Office of Transport (FOT), 2021). The railway grid totalled 4652.5 km (2870.3 km of single-track and 1782.2 km of multi-track lines).

2.3.1. Proximity models

We developed proximity models based on a literature review of ELF-MF measurement and modelling studies (see Table S2, Supplementary Material). A nonlinear least squares approach was applied to model the inverse power function between ELF-MF exposure derived from the literature and distance from the lines (see Eq. S1), with stratification by line voltage (36–150 kV and 220–380 kV) for HVPL, and number of tracks (single- and multi-track) for railway lines. Tables S3-S4 and Figs. S1-S2 present the estimated parameters and model function describing the relationship between ELF-MF exposure and distance from HVPL and railway lines.

We validated the proximity models using a subset of measurements taken inside 59 private dwellings between 2021 and 2023 as part of the Swiss non-ionising radiation monitoring project (Loizeau et al., 2024) (Fig. S3). Briefly, these measurements were collected with an ExpoM-ELF magnetic field meter for 16.7 Hz (railway power) and 50 Hz (domestic power) frequency bands. In each dwelling, 24-hour spot measurements were taken in the bedroom, alongside 10-minute spot

measurements in the living room. Bedroom and living room aggregated root mean squared (RMS) values for 16.7 Hz and 50 Hz frequency bands were compared with predicted exposure from proximity models of HVPL and railway lines, respectively.

For HVPL 220–380 kV, predicted values showed a moderate correlation with measured exposure, both in bedrooms (Spearman's rho [r] = 0.60, $p < 0.001$) and living rooms ($r = 0.67$, p -value = 0.003). Measured ELF-MF exposure decreased with distance from HVPL only for lines 220–380 kV (Fig. S4). In contrast, distance from HVPL 36–150 kV was not correlated with measured ELF-MF exposure (living rooms: $r = 0.05$, p -value = 0.783), likely because other sources (e.g., household appliances, nearby electrical infrastructure, or underground cables) dominated the measured exposure levels. Based on these results, we did not pursue exposure estimation using our proximity models for lines 36–150 kV. For railway lines, strong correlations were observed between predicted and measured exposure from single-track (bedroom: $r = 0.85$, $p < 0.001$; living room: $r = 0.88$, $p < 0.001$) and multi-track lines (bedroom: $r = 0.86$, p -value < 0.001 ; living room: $r = 0.83$, p -value < 0.001) (Fig. S5).

2.3.2. Long-term ELF-MF exposure

Using geo-coded residential locations from the SNC, we calculated, for each census year, the distance from each individual's residence to the nearest HVPL 220–380 kV or railway line and estimated ELF-MF exposure (in μT) based on our proximity models. To account for simultaneous exposure to both sources and to evaluate potential additive effects, we derived a combined exposure metric following the approach described in the ICNIRP guidelines (International Commission on Non-Ionizing Radiation Protection (ICNIRP), 2010). In this approach, exposures from each source are normalised by their respective ICNIRP reference levels (200 μT for HVPL operating at 50 Hz and 200 μT for railway lines operating at 16.7 Hz) and summed:

$$\text{Combined exposure}(\%) = \left(\frac{\text{HVPL}}{200} + \frac{\text{RL}}{300} \right) * 100(1)$$

To capture long-term exposure while accounting for residential mobility, we divided the follow-up into four intervals (2001–2005, 2006–2010, 2011–2015, and 2016–2018). We calculated a time-weighted average exposure over the 10-year window preceding each interval (1991–2001, 1996–2006, 2001–2011, and 2006–2016, respectively) to reflect the long induction periods typical of neurodegenerative diseases, for which outcomes such as mortality may take years to manifest. We reconstructed individual residential histories within each exposure window, estimated the number of years spent at each address, and computed the average exposure weighted by duration of residence, thereby reducing exposure misclassification related to residential mobility.

Residential mobility histories were available annually from 2010 onward. Individuals were classified as movers if their geocodes differed between two consecutive censuses, and moves were assumed to occur at the midpoint between census dates. For earlier years, residential mobility was inferred from changes in geocoded addresses across the 1991, 2001, and 2010 censuses. For years without a census (1996 and 2006), we reconstructed residential location using the geocodes from the preceding and following census, along with the responses to a question on community of residence five years prior. For 1996, individuals with different 1991 and 2001 geocodes were considered movers. If their reported municipality of residence in 1991 matched that reported in 1996, the move was assumed to have occurred between 1996 and 2001; if the 1996 municipality matched that reported in 2001, the move was assumed to have occurred between 1991 and 1996. For 2006, movers whose municipality matched 2001 were assumed to move between 2006 and 2010, while those matching 2010 between 2001 and 2006.

2.4. Covariates

We used three sets of covariates in multivariable-adjusted analyses: minimally adjusted, sociodemographic, and environmental co-exposures. Minimally adjusted models accounted for age (years) and strata(sex) (i.e., biological sex as male/female). Sociodemographic models further adjusted for nationality (Swiss/other), mother tongue (German/French/Italian/other), civil status (married/single/widowed/divorced), education level (compulsory school/upper secondary/tertiary education), and local-level socioeconomic position (Swiss-SEP, based on the 50 nearest households). We used the Swiss-SEP 1, based on decennial census data, for the 2001–2005 and 2006–2010 intervals, and the hybrid version based on both decennial and registry-based census data (Swiss-SEP 3) for 2011–2015 and 2016–2018 intervals (Panczak et al., 2023). For environmental co-exposures, we incorporated factors that have been related to NDD (Wang et al., 2017; Aravindan et al., 2024; Jones et al., 2025), including degree of urbanicity (urban/peri-urban/rural) as a proxy for pesticide or chemical exposures, air pollution, transportation noise, and greenness. Variables linked to residential address (Swiss-SEP, degree of urbanicity, air pollution, transportation noise, and greenness) as well as civil status, were treated as time-varying covariates and updated at the beginning of each follow-up interval.

As an indicator of air pollution, we used annual average nitrogen dioxide (NO_2) concentrations ($\mu\text{g}/\text{m}^3$) from Swiss-wide models at a 100m $\times$ 100m resolution (de Hoogh et al., 2019). Modelled NO_2 data were available for 2005–2018. For years 2001–2004, concentrations were back-extrapolated from the 2005 modelled spatial distribution using correction factors based on the ratio of each year's mean NO_2 concentration across all nationwide measurement stations to that of 2005. We then calculated time-weighted annual averages of NO_2 exposure for each follow-up interval.

Transportation noise was estimated using the maximum day-evening-night level ($L_{\text{den,Max}}$) from either road traffic or railway sources, modelled at the maximum exposed residential building façade of each dwelling with Swiss-wide three-dimensional propagation models. Road traffic noise was estimated with sonRoad18 model (Heutschi et al., 2018), and railway noise with the sonRAIL (Thron & Hecht, 2010), both combined with the ISO 9613–2 sound propagation model (ISO, 1996). Data were available for years 2001 (applied for 2001–2005 follow-up interval), 2011 (2011–2015 follow-up interval), and 2015 (2016–2018). For 2006, noise exposure was assigned based on residential history, using either 2001 or 2011 estimates.

Residential greenness was estimated using the median Normalised Difference Vegetation Index (NDVI) within a 300 m buffer of 250 $\times$ 250 m grid cells. We obtained annual NDVI data from the EXPANSE project (de Hoogh et al., 2025) for years 2000, 2005, 2010, and 2015. Data from these years were applied to the follow-up intervals beginning in 2001, 2006, 2011, and 2016, respectively.

2.5. Statistical analysis

We used Cox proportional hazard models to investigate the association between long-term residential ELF-MF exposure and NDD mortality outcomes. Age was used as the underlying time scale in all models to account for the age dependence of the outcomes and to properly account for left truncation due to delayed entry at different ages (Thiébaud & Bénichou, 2004). All models were stratified by sex, language region of residence (German or Rhaeto-Romansh/French/Italian), and follow-up interval. This was used to account for differences in baseline risks among groups. Specifically, stratification by language region was used to account for spatial heterogeneity in mortality patterns across Switzerland (Fig. S6), which may be related to regional differences in lifestyle, environmental exposures, and healthcare services (Singhal et al., 2025). Stratification by follow-up interval was used to control for temporal trends in mortality during the study period (Fig. S6). Separate models were fitted for ELF-MF exposure from HVPL, railway lines, and the

Table 1

Baseline (2001) characteristics of the study population by all-cause and neurodegenerative diseases mortality outcomes.

	All study population	All-cause mortality	Alzheimer's disease	Other types of dementia	Amyotrophic lateral sclerosis	Parkinson's disease	Multiple sclerosis
	N = 3555064	N = 220652	N = 28798	N = 97804	N = 3042	N = 19829	N = 3253
Age (years)							
Min.- Max.	30.00–100.00	30.00–100.00	30.72–99.87	32.47–99.98	30.05–93.97	30.59–98.23	30.03–97.49
Mean (SD)	52.90 (23.59)	77.24 (16.61)	76.60 (10.13)	77.23 (9.88)	63.50 (15.37)	74.08 (10.94)	64.13 (19.96)
Sex, n (%)							
Male	1,684,018 (47.4)	117,044 (53.0)	9863 (34.2)	34,105 (34.9)	1641 (53.9)	11,409 (57.5)	1237 (38.0)
Female	1,871,046 (52.6)	103,608 (47.0)	18,935 (65.8)	63,699 (65.1)	1401 (46.1)	8420 (42.5)	2016 (62.0)
Nationality, n (%)							
Swiss	3,119,233 (87.7)	205,604 (93.2)	27,131 (94.2)	93,312 (95.4)	2774 (91.2)	18,724 (94.4)	3090 (95.0)
Other	435,831 (12.3)	15,048 (6.8)	1667 (5.8)	4492 (4.6)	268 (8.8)	1105 (5.6)	163 (5.0)
Mother tongue, n (%)							
German	2,398,252 (67.5)	153,059 (69.4)	15,746 (54.7)	75,107 (76.8)	2083 (68.5)	14,379 (72.5)	2389 (73.4)
French	693,975 (19.5)	47,187 (21.4)	9950 (34.6)	15,738 (16.1)	623 (20.5)	3814 (19.2)	648 (19.9)
Italian	261,367 (7.4)	14,467 (6.6)	2493 (8.7)	4859 (5.0)	216 (7.1)	1130 (5.7)	136 (4.2)
Other	201,470 (5.7)	5939 (2.7)	609 (2.1)	2100 (2.1)	120 (3.9)	506 (2.6)	80 (2.5)
Civil Status, n (%)							
Single	460,270 (12.9)	21,082 (9.6)	2091 (7.3)	8182 (8.4)	234 (7.7)	1472 (7.4)	390 (12.0)
Married	2,479,443 (69.7)	117,493 (53.2)	16,076 (55.8)	50,548 (51.7)	2229 (73.3)	13,256 (66.9)	2057 (63.2)
Widowed	316,828 (8.9)	66,256 (30.0)	8970 (31.1)	33,125 (33.9)	366 (12.0)	4071 (20.5)	481 (14.8)
Divorced	298,523 (8.4)	15,821 (7.2)	1661 (5.8)	5949 (6.1)	213 (7.0)	1030 (5.2)	325 (10.0)
Education level, n (%)							
Compulsory level	857,678 (24.1)	92,030 (41.7)	12,889 (44.8)	44,059 (45.0)	763 (25.1)	6992 (35.3)	988 (30.4)
Upper secondary level	1,949,887 (54.8)	101,213 (45.9)	12,599 (43.7)	43,772 (44.8)	1631 (53.6)	9520 (48.0)	1764 (54.2)
Tertiary level	747,499 (21.0)	27,409 (12.4)	3310 (11.5)	9973 (10.2)	648 (21.3)	3317 (16.7)	501 (15.4)
Swiss-SEP							
Min.- Max.	0.00–100.00	2.16–97.89	5.93–97.38	4.28–97.81	19.84–92.68	11.51–96.33	11.51–94.72
Mean (SD)	63.47 (14.31)	62.41 (13.85)	62.73 (14.20)	63.45 (13.87)	64.54 (14.44)	63.57 (14.21)	63.93 (14.38)
Language region							
German or Rhaeto-Romansh	2,604,555 (73.3)	159,006 (72.1)	15,776 (54.8)	78,143 (79.9)	2225 (73.1)	14,901 (75.1)	2464 (75.7)
French	785,993 (22.1)	51,013 (23.1)	10,938 (38.0)	16,443 (16.8)	677 (22.3)	4131 (20.8)	682 (21.0)
Italian	164,516 (4.6)	10,633 (4.8)	2084 (7.2)	3218 (3.3)	140 (4.6)	797 (4.0)	107 (3.3)

N = number of observations; Min. = minimum; Max. = maximum; SD = standard deviation; Swiss-SEP= Swiss socioeconomic position index.

combined metric. We estimated hazard ratios (HR) for a 1 μT increase in HVPL and railway lines exposure, and for 1% increase in combined exposure. The combined exposure is expressed as the sum of the source-specific exposures normalised by their respective ICNIRP reference levels (see Eq.1). All analyses were conducted in R (version 4.5.1) within RStudio (2025.5.1.513).

To explore potential effect modification, we conducted subgroup analyses for AD and other types of dementia (OTD) mortality by sex, age group (≤ 75 years old), and socioeconomic position (Swiss-SEP median split). Effect modification was tested using likelihood ratio tests (LRT) comparing models with and without an interaction term between ELF-MF exposure and an indicator variable for each subgroup. Subgroup analysis by sex allowed exploration of biological or diagnostic differences between males and females. Subgroup analysis by age addressed the possibility that ELF-MF exposure might have a stronger effect at younger ages, as it has been observed in previous studies (Andel et al., 2010; Frei et al., 2013). Lastly, subgroup analysis by socioeconomic position was motivated by its potential role as a modifier of vulnerability, given that Swiss-SEP may be related to both residential location (and thus exposure) and disease detection.

Several sensitivity analyses were conducted to evaluate the

robustness of the results. First, ELF-MF exposure was modelled as a categorical variable to explore potential non-linear exposure–response relationships. Exposure was classified into four categories: $<0.05 \mu\text{T}$ (reference), $0.05\text{--}<0.10 \mu\text{T}$, $0.10\text{--}<0.3$ (or 0.4) μT , and ≥ 0.3 (or 0.4) μT . Second, we used distance corridors from nearest HVPL or railway lines at baseline (≥ 600 m, 200–599 m, 50–199 m, and 0–49 m), replicating the methodology used in the previous Swiss study (Huss et al., 2009), but here with an extended follow-up. Third, we restricted the analysis to individuals who had ever lived within 1 km of HVPL or railway lines during the follow-up ($n = 2\,800\,562$; 78.8% of the study population), to assess residual confounding by unmeasured factors that may differ between populations living close to the lines and those living farther away, which could make the latter an inappropriate reference population. Fourth, we repeated the analyses in the subgroup of individuals who never changed residence since 1990 (non-movers; $n = 1\,448\,877$; 40.8%) to assess residual exposure misclassification arising from residential mobility and uncertainty regarding unknown latency and induction periods for NDD. Fifth, analyses were repeated considering only cases where NDD outcomes were listed as the primary cause of death. Finally, we investigated associations with negative control outcomes that are unlikely to be affected by ELF-MF exposure but may be related

Table 2

Environmental co-exposure of the study population by all-cause and neurodegenerative diseases mortality outcomes at baseline (2001).

	All study population	All-cause mortality	Alzheimer's disease	Other types of dementia	Amyotrophic lateral sclerosis	Parkinson's disease	Multiple sclerosis
	N = 3555064	N = 220652	N = 28798	N = 97804	N = 3042	N = 19829	N = 3253
Degree of urbanicity, n (%)							
Urban	996,767 (28.0)	75,296 (34.1)	10,503 (36.5)	35,537 (36.3)	921 (30.3)	6259 (31.6)	1029 (31.6)
Peri-urban	1,608,051 (45.2)	86,578 (39.2)	11,395 (39.6)	38,252 (39.1)	1364 (44.8)	8153 (41.1)	1418 (43.6)
Rural	950,246 (26.7)	58,778 (26.6)	6900 (24.0)	24,015 (24.6)	757 (24.9)	5417 (27.3)	806 (24.8)
NO₂ (µg/m³)							
Min.- Max.	0.00–67.06	0.00–66.89	0.00–64.90	0.00–66.89	2.01–59.59	0.19–64.90	0.74–60.89
Mean (SD)	20.65 (10.64)	21.61 (11.64)	22.11 (12.22)	21.71 (11.30)	20.79 (10.75)	20.97 (10.90)	21.34 (10.35)
Median (IQR)	20.65 (15.76–26.40)	21.61 (16.18–27.82)	22.11 (16.55–28.77)	21.71 (16.47–27.77)	20.79 (15.86–26.61)	20.97 (15.87–26.77)	21.34 (16.28–26.63)
L_{den,Max} (dB)							
Min.- Max.	35.00–91.40	35.00–86.60	35.00–85.20	35.00–86.10	35.00–79.30	35.00–86.90	35.00–81.10
Mean (SD)	52.30 (11.30)	53.00 (11.40)	52.90 (11.20)	52.70 (11.20)	52.30 (11.18)	52.30 (11.10)	52.60 (11.10)
Median (IQR)	52.30 (46.90–58.20)	53.00 (47.60–59.00)	52.90 (47.60–58.80)	52.70 (47.40–58.60)	52.30 (46.92–58.10)	52.30 (47.00–58.10)	52.60 (47.20–58.30)
NDVI							
Min.- Max.	0.05–0.86	0.07–0.86	0.07–0.85	0.07–0.85	0.15–0.83	0.07–0.84	0.11–0.82
Mean (SD)	0.59 (0.15)	0.57 (0.16)	0.57 (0.16)	0.57 (0.15)	0.59 (0.15)	0.58 (0.15)	0.58 (0.14)
Median (IQR)	0.59 (0.51–0.66)	0.57 (0.49–0.65)	0.57 (0.48–0.64)	0.57 (0.50–0.65)	0.59 (0.52–0.66)	0.58 (0.51–0.66)	0.58 (0.51–0.65)

N = number of observations; Min. = minimum; Max. = maximum; NO₂ = nitrogen dioxide; SD = standard deviation; IQR = interquartile range; L_{den,Max} = maximum day-evening-night noise level (at the maximum exposed façade per dwelling) from either road traffic or railway sources; NDVI = normalised difference vegetation index.

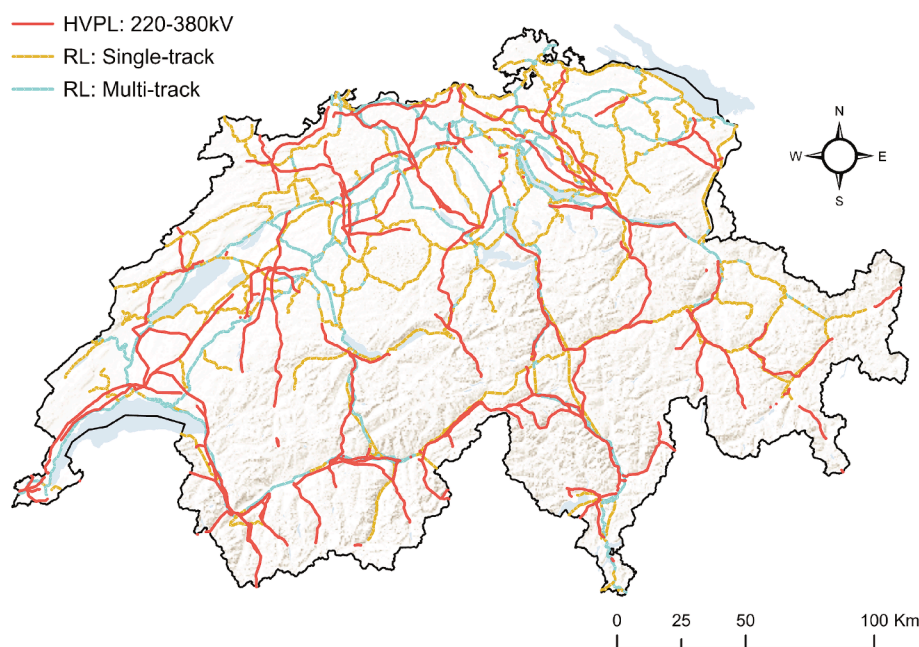


Fig. 1. Swiss high-voltage (220–380 kV) electricity grid (red lines) and railway grid (blue lines for multi-track sections, yellow lines for single-track sections). Data sources: Swiss Terrain Landscape Model in 3D, Electricity Transmission Lines Sector Plan (geo.admin.ch), Railway Network (geo.admin.ch), and Federal Office of Topography (background map). Note that power lines of 36–150 kV are not included since exposure from these lines was not used for analysis. HVPL = high voltage power lines; RL = railway lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to socioeconomic position or lifestyle factors: trachea, bronchus, or lung cancer (ICD-10: C33–C34), oesophageal cancer (C15), and alcoholic liver disease (K70). To further evaluate the robustness of the results to unmeasured confounding, we calculated E-values (VanderWeele & Ding, 2017) for the main results. E-values refer to the minimum estimated strength of the association between an unmeasured factor and

both exposure and outcome, conditional on the included covariates, that would be necessary to explain the observed exposure-outcome associations. In addition, we calculated population attributable fractions for the main exposure-outcome associations following the approach described by Perez and Künzli (2009).

We assessed potential multicollinearity between covariates with

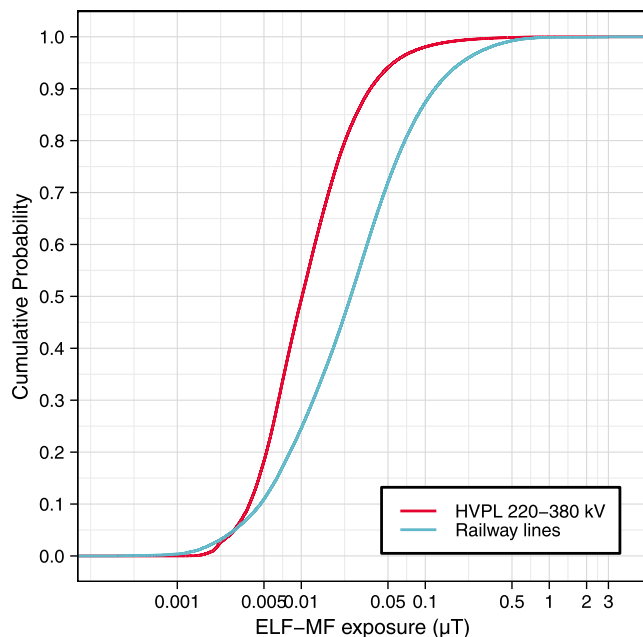


Fig. 2. Cumulative probability distribution functions of estimated long-term residential ELF-MF exposure from high voltage power lines (HVPL) and railway lines (RL). X-axis was log-transformed.

correlation matrices (Fig. S7) and by calculating variance inflation factors (VIFs) for full adjusted models. VIFs values for all variables included in the models ranged from 1.00 to 1.49, indicating small multicollinearity. We assessed violations of the proportional hazard assumption using scaled Schoenfeld residuals plots for each covariate. Visual inspection revealed no clear systematic trends over time.

3. Results

A total of 3 555 064 individuals were followed between 1 January 2001 and 31 December 2018, contributing to 55 377 543 person-years. During follow-up, 146 655 deaths from NDD were reported, including 28 798 from AD, 97 804 from OTD, 3 042 from ALS, 19 829 from PD, and 3 253 from MS. At baseline, the study population was predominantly female (52.6%) with a mean age of 52.9 years (Table 1). Most individuals were Swiss nationals (87.7%), lived in German or Rhaeto-Romansh language regions (73.3%), and had German as their mother tongue (67.5%). Most individuals were married (69.7%) and had completed upper secondary education (54.8%), with a mean Swiss-SEP of 63.5. The distribution of environmental co-exposures for the study population is shown in Table 2.

Fig. 1 shows the Swiss high-voltage electricity (HVPL 220–380 kV) and railway grids used to estimate residential ELF-MF exposure. Throughout follow-up, median long-term exposure from HVPL was 0.01 μ T (interquartile range [IQR] = 0.01 μ T), with a mean of 0.02 μ T (standard deviation [SD] = 0.04 μ T) and 95th and 99th percentiles of 0.05 μ T and 0.15 μ T, respectively (Fig. 2). Only 0.3% of the individuals had long-term exposure from HVPL above 0.30 μ T. In comparison, exposure from railway lines was higher, with a median of 0.03 μ T (IQR = 0.05 μ T), a mean of 0.06 μ T (SD = 0.12 μ T), and 95th and 99th percentiles of 0.20 μ T and 0.46 μ T (Fig. 2). Long-term exposure from railway lines above 0.30 μ T were observed in 2.4% of the individuals. Combined exposure, expressed as the sum of the source-specific exposures normalised by their respective ICNIRP reference levels, had a median of 0.03% (IQR = 0.05%), a mean of 0.03% (SD = 0.02%), and 95th and 99th percentiles of 0.09% and 0.18%. The distribution of ELF-MF exposure was similar across NDD mortality outcomes (Table S5). Long-term residential ELF-MF exposure from HVPL and railway lines

were not correlated (Spearman's rho [r] = -0.04). Exposure from railway lines was positively correlated with transportation noise (r = 0.30) and air pollution (r = 0.33) and negatively correlated with residential greenness (r = -0.32). In contrast, exposure from HVPL showed no correlation with transportation noise (r = 0.03), air pollution (r = 0.02), or residential greenness (r = -0.02) (Fig. S7).

3.1. Main results

Long-term residential ELF-MF exposure from HVPL was associated with a higher risk of mortality from AD and OTD, with consistent positive association estimates across all covariate sets (Fig. 3). After accounting for sociodemographic and environmental co-exposures, 1 μ T increase in HVPL exposure was associated with 54% higher AD mortality risk (95% CI 1.23–1.92). For OTD, associations were somewhat weaker: 1 μ T increase in exposure was associated with 31% higher mortality risk (95% CI 1.13–1.52).

Associations between ELF-MF from railway lines and mortality from AD and OTD were less consistent than those observed for HVPL. For AD, railway lines exposure was positively associated with mortality in minimally adjusted models (HR = 1.15, 95% CI 1.06–1.24) and in models adjusted for sociodemographic factors (HR = 1.15, 95% CI 1.06–1.25) but attenuated after including environmental co-exposures (HR = 1.08, 95% CI 0.99–1.18) (Fig. 3). A similar pattern was observed for OTD. A closer inspection indicated that the attenuation was mainly driven by adjustment for transportation noise exposure (Fig. S8), which was positively related to dementia outcomes (Table S6).

The result pattern for the combined exposure metric tended to follow that observed for railway lines, and the association estimates generally fell between those observed for HVPL and railway lines. An absolute increase of 1% in combined exposure in relation to ICNIRP reference levels was associated with an HR of 1.46 (95% CI 1.16–1.84) and 1.06 (95% CI 0.93–1.21) for AD and OTD, respectively.

For ALS, PD, and MS, we observed consistent null results across all exposure metrics and covariate sets, indicating no evidence of association (Fig. 3).

3.2. Subgroup analyses

Associations between ELF-MF exposure and mortality from AD and OTD were similar in males and females, with slightly stronger estimates among females (Table 3). Including an interaction between ELF-MF exposure and sex did not improve model fit (Table S7).

Age appeared to modify the association between ELF-MF exposure and mortality from AD and OTD (Table 3). For AD, somewhat stronger estimates were observed among individuals older than 75 years (HR per 1 μ T increase in HVPL exposure = 1.58, 95% CI 1.25–2.01), compared with younger individuals (HR = 1.31, 95% CI 0.71–2.43), although including an interaction between HVPL exposure and age group did not explain additional variability in the outcome (Table S7). For OTD, positive associations were observed only among individuals older than 75 years (HR per 1 μ T increase of HVPL exposure = 1.36; 95% CI 1.17–1.59) and the inclusion of an interaction term between HVPL exposure and age group improved the model fit (LRT p = 0.029).

There was variation in the association estimates for HVPL exposure across socioeconomic groups (Table 3). However, the confidence intervals between groups overlapped, and the inclusion of an interaction term between HVPL exposure and socioeconomic position did not improve model fit for AD or OTD mortality (Table S7). For OTD, railway lines exposure was associated with a lower mortality risk among participants with lower compared to higher socioeconomic position (LRT p -value < 0.001), indicating possible competing risks given the advanced age at which dementia cases were observed (mean age at baseline of 77.23 years, Table 1).

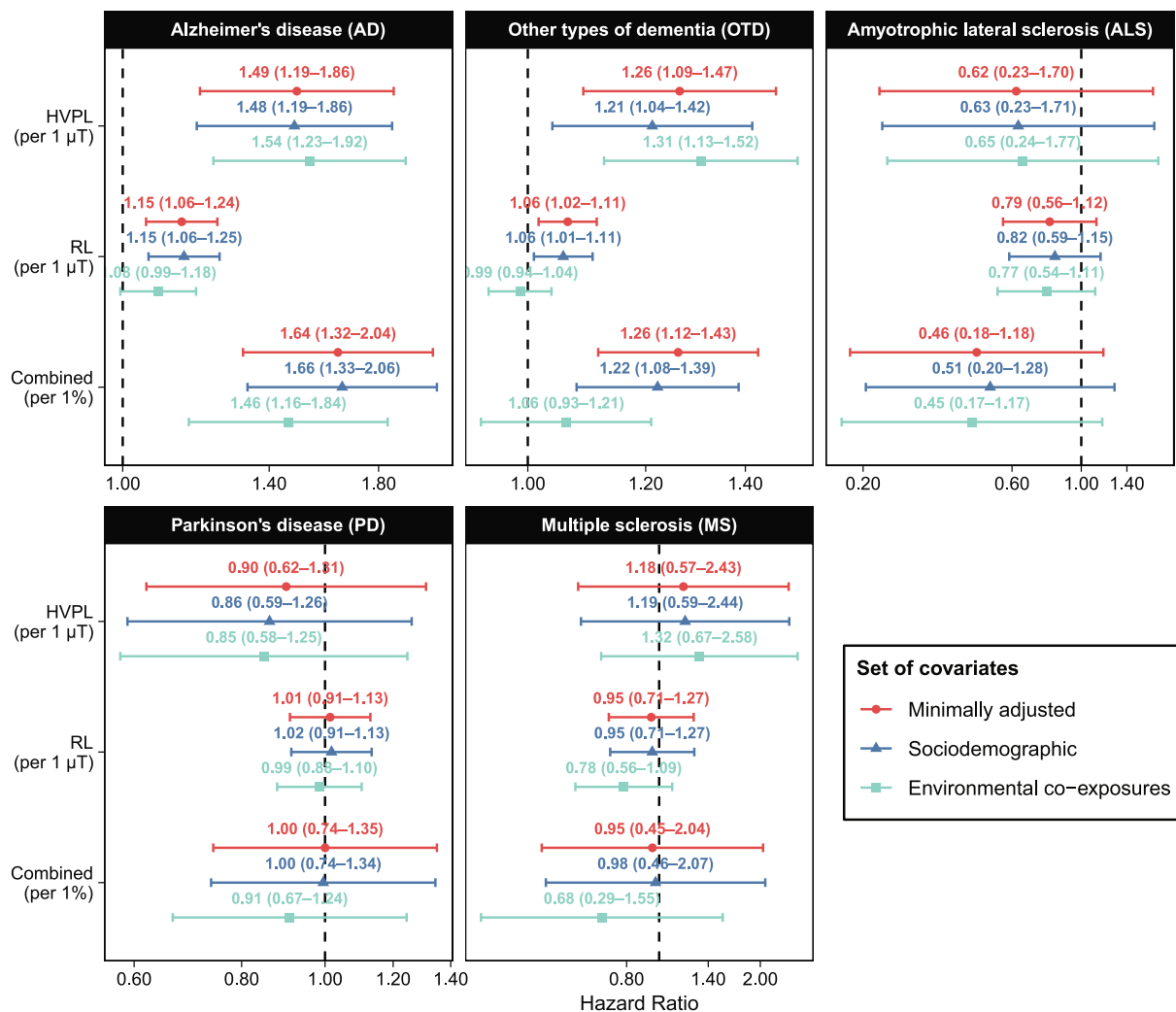


Fig. 3. Association estimates between long-term residential ELF-MF exposure and NDD mortality. Estimates are expressed as HR (95% CI) from Cox proportional hazards models with age as the underlying time scale and strata (sex, language region of residence, and follow-up interval). Results are shown for each exposure source (HVPL, RL, and combined) and for three covariate sets: minimally adjusted, sociodemographic (+nationality, mother tongue, civil status, education level, local-level Swiss-SEP), and environmental co-exposures (+residential degree of urbanicity, NO₂, Lden,Max, and NDVI). X-axis was log-transformed. HR = hazard ratio; CI = confidence interval; ELF-MF = extremely low frequency magnetic fields; NDD = neurodegenerative diseases; HVPL = high voltage power lines; RL = railway lines; NO₂ = nitrogen dioxide; Lden,Max = maximum day-evening-night noise level (at the maximum exposed façade per dwelling) from either road traffic or railway sources; NDVI = normalised difference vegetation index.

3.3. Sensitivity analyses

When ELF-MF exposure from HVPL was treated as categorical in the models, we observed a positive trend in AD and OTD mortality risk across the intermediate exposure categories, but not for the highest category (Table 4, Table S8). Analysis using distance corridors to the nearest HVPL or railway lines at baseline showed a pattern consistent with the main analysis (Table S9). We observed virtually no differences in the results when restricting the analysis to individuals who had ever lived within 1 km of HVPL or railway lines during follow-up compared with the main analysis (Fig. S9). Similarly, restricting the analysis to non-movers (Fig. S10) or to NDD mortality cases listed only as the primary cause of death (Fig. S11) yielded similar results to the main analysis, but with slightly lower estimates and wider confidence intervals, reflecting reduced statistical power.

We observed no consistent association between ELF-MF exposure and negative control outcomes (Table S10), although a positive association was observed for trachea, bronchus, or lung cancer mortality (HR per 1 μ T increase in HVPL exposure = 1.19; 95% CI 0.99–1.43). The E-values for the observed association between HVPL exposure and AD (HR

per 1 μ T increase = 1.54; 95% CI 1.23–1.92) and OTD mortality risk (HR = 1.31, 95% CI 1.13–1.52) were 2.45 (lower CI 1.76) and 1.95 (lower CI 1.51), respectively, indicating that an unmeasured confounder, after accounting for the covariates in our model, would need to be associated with both HVPL and AD or OTD by moderate to strong associations to fully explain the observed results.

4. Discussion

In this large-scale, nationwide cohort study with nearly two decades of follow-up, we observed a positive association between long-term residential ELF-MF exposure from high voltage power lines and mortality from Alzheimer's disease and other types of dementia. For the first time, we investigated neurodegenerative diseases risk in relation to ELF-MF exposure from railway lines in the general population, while also assessing combined exposure from outdoor ELF-MF sources. These associations were less consistent and largely null after adjusting for transportation noise exposure. In addition, our study found robust evidence that residential ELF-MF is not associated with mortality from amyotrophic lateral sclerosis, Parkinson's disease, or multiple sclerosis.

Table 3

Association estimates* from main and subgroup analyses between long-term residential ELF-MF exposure and mortality from Alzheimer's disease and other types of dementia.

	N	Number of deaths	Number of person-years	Exposure from HVPL HR (95% CI)	Exposure from RL HR (95% CI)	Combined exposure HR (95% CI)
Alzheimer's disease (AD)						
Full study population	12 632 723	28 798	55 377 543	1.54 (1.23–1.92)	1.08 (0.99–1.18)	1.46 (1.16–1.84)
Males	5 918 465	9 863	25 883 500	1.44 (0.95–2.16)	1.03 (0.88–1.21)	1.25 (0.83–1.90)
Females	6 714 258	18 935	29 494 043	1.58 (1.22–2.05)	1.11 (1.00–1.23)	1.57 (1.20–2.06)
Population ≤ 75 years old	10 586 577	3 379	47 729 159	1.31 (0.71–2.43)	1.04 (0.79–1.37)	1.27 (0.63–2.55)
Population > 75 years old	2 046 146	25 419	7 648 384	1.58 (1.25–2.01)	1.09 (0.99–1.19)	1.49 (1.17–1.90)
Population with Swiss-SEP ≤ median	6 316 387	15 222	27 575 754	1.81 (1.35–2.42)	1.07 (0.94–1.23)	1.60 (1.14–2.23)
Population with Swiss-SEP > median	6 316 336	13 576	27 801 789	1.29 (0.89–1.86)	1.08 (0.97–1.22)	1.34 (0.98–1.83)
Other types of dementia (OTD)						
Full study population	12 632 723	97 804	55 377 543	1.31 (1.13–1.52)	0.99 (0.94–1.04)	1.06 (0.93–1.21)
Males	5 918 465	34 105	25 883 500	1.26 (0.97–1.63)	0.94 (0.86–1.03)	0.94 (0.74–1.18)
Females	6 714 258	63 699	29 494 043	1.33 (1.11–1.60)	1.01 (0.95–1.07)	1.13 (0.96–1.32)
Population ≤ 75 years old	10 586 577	6 905	47 729 159	0.81 (0.43–1.52)*	0.92 (0.75–1.12)	0.75 (0.43–1.30)
Population > 75 years old	2 046 146	90 899	7 648 384	1.36 (1.17–1.59)*	0.99 (0.94–1.04)	1.09 (0.95–1.24)
Population with Swiss-SEP ≤ median	6 316 387	49 071	27 575 754	1.23 (1.00–1.53)	0.92 (0.84–1.00)*	0.90 (0.72–1.11)*
Population with Swiss-SEP > median	6 316 336	48 733	27 801 789	1.42 (1.17–1.73)	1.03 (0.97–1.09)*	1.18 (1.00–1.39)*

*Hazard ratios (HR) and 95% confidence intervals (CI) from Cox proportional hazards models with age as the underlying time scale, strata (sex, language region of residence, and follow-up interval), and adjusted for nationality, mother tongue, civil status, education level, local-level Swiss-SEP, residential degree of urbanicity, NO₂, L_{den}Max, and NDVI.

ELF-MF = extremely low frequency magnetic fields; N = number of observations; HVPL = high voltage power lines; RL = railway lines; Swiss-SEP = Swiss socioeconomic position index; NO₂ = nitrogen dioxide; L_{den}Max = maximum day-evening-night noise level (at the maximum exposed façade per dwelling) from either road traffic or railway sources; NDVI = normalised difference vegetation index.

* Likelihood ratio test p-value < 0.05.

Electrical appliances and indoor wiring are the most common sources of ELF-MF exposure in indoor environments for the general population, but such exposures are typically intermittent and of short duration (Schüz et al., 2000; Gajšek et al., 2016). In contrast, proximity to outdoor sources like high voltage power lines and railway infrastructure represents a better indicator of long-term exposure in the general population (Amoon et al., 2020) and children (Struchen et al., 2016). For instance, median residential exposure in Swiss homes near HVPL was found to be 0.37 µT (Loizeau et al., 2024). In our study, residential proximity to HVPL was very rare and less than 1% of the population had modelled long-term magnetic field levels above 0.30 µT. Exposure to ELF-MF from railway lines has been less well characterised among the general population, but median exposure levels of 0.48 µT have been observed in train stations (Loizeau et al., 2024). In our study population, about 2.4% of individuals had modelled residential long-term magnetic field levels above 0.30 µT. Similarly, a measurement study conducted in residences with children in western Germany reported magnetic field levels above 0.2 µT at 16.7 Hz in only 2.2% of the homes measured, all of which were located less than 50 m from a railroad (Schüz et al., 2000). Another study using on personal exposure measurements reported median magnetic fields of 0.10 µT in people living next to railway lines (Brix et al., 2001).

Our findings on Alzheimer's disease mortality risk are consistent with the earlier analysis of the Swiss National Cohort (Huss et al., 2009). Although partly overlapping in their study base, there are several differences between the two studies. Huss et al. (2009) analysed mortality between 2000 and 2005, while we extended follow-up to 2018. They defined exposure using baseline distance corridors and estimated risks for different durations of residence. In contrast, we used validated residential proximity models and, given the longer follow-up, treated exposure as time-varying. In addition, we calculated time-weighted average exposures over 10-year exposure windows preceding each exposure update to reflect long-term exposure. We also accounted for environmental co-exposures not considered previously, including transportation noise and residential greenness.

Our findings also align with repeatedly observed higher dementia risk among workers exposed to high ELF-MF levels (Jalilian et al., 2018;

Gunnarsson & Bodin, 2019; Huang et al., 2020; Health Council of the Netherlands, 2022). However, a direct comparison with occupational studies is not entirely straightforward, as occupational settings often involve higher exposure levels, different exposure patterns, and potential co-exposures. In contrast, our study shows some discrepancies with other studies considering exposure from residential settings, which could be partly explained by differences in outcome definition and exposure assessment. For example, a register-based case-control study in Denmark (Frei et al., 2013) found an increased risk only among individuals diagnosed after 2003 and between 65 and 75 years of age. Similarly, a study in Milan (Gervasi et al., 2019) found only a modest risk increase, though it relied on recent rather than long-term residential exposure. Another case-control study examined cognitive impairment instead of dementia outcomes and found no association with proximity to power lines (Li et al., 2002). Lastly, a recent study in Finland found no AD risk increase for people exposed to ELF-MF from indoor transformer stations (Liimatainen et al., 2025).

The biological pathways that could explain our results for dementia remain unclear. Several mechanisms for neurodegeneration have been proposed, including alterations in neuronal ion channels (Bertagna et al., 2021), epigenetic dysregulation (Giorgi & Del Re, 2021), and oxidative stress (Schuermann & Mevissen, 2021). Yet, current evidence supporting the involvement of any of these mechanisms remains weak (Wyszkowska & Pritchard, 2022; SCHEER (Scientific Committee on Health, Environmental and Emerging Risks), 2024). Moreover, findings from experimental studies are inconsistent and some even report beneficial effects following ELF-MF exposure (Health Council of the Netherlands, 2022).

Our findings for ALS are consistent with the existing body of evidence indicating no association with residential ELF-MF exposure (Huss et al., 2009; Marcilio et al., 2011; Frei et al., 2013; Seelen et al., 2014; Vinceti et al., 2017; Filippini et al., 2021). Weak-to-moderate increased risks of ALS have been observed in occupations with high ELF-MF exposure, although available meta-analyses show high heterogeneity and indications of small study effects as measured with the funnel plot asymmetry (Huss et al., 2018; Gunnarsson & Bodin, 2019; Jalilian et al., 2021; Health Council of the Netherlands, 2022). Regarding multiple

Table 4

Association estimates* for neurodegenerative disease mortality by categories of long-term residential ELF-MF exposure.

	Exposure from HVPL				Exposure from RL			
	N	Number of deaths	Number of person-years	HR (95% CI)	N	Number of deaths	Number of person-years	HR (95% CI)
Alzheimer's disease (AD)								
ELF-MF < 0.05 μ T	11,883,632	27,100	52,090,028	Ref.	9,090,684	20,285	39,831,362	Ref.
ELF-MF 0.05–<0.10 μ T	502,696	1130	2,206,660	1.11 (1.04–1.17)	1,944,933	4518	8,546,236	1.00 (0.96–1.03)
ELF-MF 0.10–<0.30 μ T	203,873	480	894,792	1.19 (1.09–1.30)	1,288,545	3187	5,654,132	1.02 (0.98–1.06)
ELF-MF $\geq$ 0.30 μ T	42,522	88	186,063	1.07 (0.87–1.32)	308,561	808	1,345,813	1.01 (0.94–1.09)
Other types of dementia (OTD)								
ELF-MF < 0.05 μ T	11,883,632	92,805	52,090,028	Ref.	9,090,684	67,900	39,831,362	Ref.
ELF-MF 0.05–<0.10 μ T	502,696	3366	2,206,660	1.06 (1.03–1.10)	1,944,933	16,259	8,546,236	1.02 (1.00–1.04)
ELF-MF 0.10–<0.30 μ T	203,873	1366	894,792	1.11 (1.05–1.17)	1,288,545	10,941	5,654,132	1.00 (0.98–1.02)
ELF-MF $\geq$ 0.30 μ T	42,522	267	186,063	1.08 (0.96–1.22)	308,561	2704	1,345,813	0.96 (0.92–1.00)
Amyotrophic lateral sclerosis (ALS)								
ELF-MF < 0.05 μ T	11,883,632	2879	52,090,028	Ref.	9,090,684	2221	39,831,362	Ref.
ELF-MF 0.05–<0.10 μ T	502,696	108	2,206,660	0.94 (0.77–1.14)	1,944,933	464	8,546,236	1.00 (0.90–1.11)
ELF-MF 0.10–<0.30 μ T	203,873	49	894,792	1.05 (0.79–1.39)	1,288,545	286	5,654,132	0.92 (0.81–1.04)
ELF-MF $\geq$ 0.30 μ T	42,522	6	186,063	0.60 (0.27–1.34)	308,561	71	1,345,813	0.89 (0.70–1.14)
Parkinson's disease (PD)								
ELF-MF < 0.05 μ T	11,883,632	18,780	52,090,028	Ref.	9,090,684	14,080	39,831,362	Ref.
ELF-MF 0.05–<0.10 μ T	502,696	702	2,206,660	1.00 (0.92–1.08)	1,944,933	3122	8,546,236	1.02 (0.98–1.06)
ELF-MF 0.10–<0.30 μ T	203,873	301	894,792	1.07 (0.95–1.20)	1,288,545	2121	5,654,132	1.01 (0.96–1.06)
ELF-MF $\geq$ 0.30 μ T	42,522	46	186,063	0.78 (0.58–1.04)	308,561	506	1,345,813	0.93 (0.85–1.02)
Multiple sclerosis (MS)								
ELF-MF < 0.05 μ T	11,883,632	3083	52,090,028	Ref.	9,090,684	2305	39,831,362	Ref.
ELF-MF 0.05–<0.10 μ T	502,696	113	2,206,660	0.97 (0.80–1.17)	1,944,933	509	8,546,236	0.99 (0.90–1.09)
ELF-MF 0.10–<0.30 μ T	203,873	46	894,792	0.98 (0.73–1.31)	1,288,545	363	5,654,132	1.04 (0.92–1.16)
ELF-MF $\geq$ 0.30 μ T	42,522	11	186,063	1.12 (0.62–2.02)	308,561	76	1,345,813	0.83 (0.66–1.06)

*Hazard ratios (HR) and 95% confidence intervals (CI) from Cox proportional hazards models with age as the underlying time scale, strata(sex, language region of residence, and follow-up interval), and adjusted for nationality, mother tongue, civil status, education level, local-level Swiss-SEP, residential degree of urbanicity, NO₂, L_{den}Max, and NDVI.

ELF-MF = extremely low frequency magnetic fields; HVPL = high voltage power lines; RL = railway lines; N = number of observations; Swiss-SEP=Swiss socio-economic position index; NO₂ = nitrogen dioxide; L_{den}Max = maximum day-evening-night noise level (at the maximum exposed façade per dwelling) from either road traffic or railway sources; NDVI = normalised difference vegetation index.

sclerosis, only a few studies have been conducted, none of which have found evidence of an association, consistent with our findings (Frei et al., 2013; Health Council of the Netherlands, 2022). Similarly, our results align with the literature showing no association between either residential (Huss et al., 2009; Frei et al., 2013; Gervasi et al., 2019) or occupational exposure and Parkinson's disease risk (Huss et al., 2015; Gunnarsson & Bodin, 2019; Health Council of the Netherlands, 2022).

4.1. Strengths and limitations

To our knowledge, the study reported here is the largest investigation to date of the association between ELF-MF in the general population and the risk of neurodegenerative diseases. Using nationwide data, we

were able to study rare outcomes in a prospective cohort with sufficient statistical power. By incorporating exposure data over 10-year windows, we could better align relevant exposure periods with disease progression, allowing for the evaluation of long-term associations in diseases with long latency and slow progression. We also had access to up to 25 years of residential history, which enabled us to reduce potential exposure misclassification related to residential mobility. This was supported by the consistency of results between the main and non-mover analyses. Another strength is that this is the first study to incorporate railway lines as a potential contributor to ELF-MF exposure in the general population. While previous occupational studies have considered ELF-MF exposure from railways (Röösli et al., 2007), this source has been overlooked in population-based studies. By also exploring the

combined effects from different sources, our study provides a novel approach for assessing potential additive effects relevant to ELF-MF exposure. The combined exposure, by design, assigned more weight to magnetic fields from higher frequencies, following ICNIRP guidelines (HVPL operating at 50 Hz contributes 1.5x more per unit than railway lines operating at 16.7 Hz; see Eq.1), although we do not know whether this summation approach is appropriate in the low exposure range where the biological mechanism is unknown. Lastly, our analyses accounted for a comprehensive set of covariates, including key environmental co-exposures such as degree of urbanicity, air pollution, transportation noise, and residential greenness, thereby strengthening the validity of our findings.

Within the limitations of this study, exposure misclassification is an important aspect to consider. First, data on power transmission and railway grids were not available for different years, so time-varying exposure only accounted for residential mobility and not for changes in the infrastructure of the lines. In Switzerland, power and railway grids are long-established networks, so any changes throughout follow-up likely did not introduce large exposure misclassification. Second, our exposure assessment approach relied on proximity models that used distance as a proxy for ELF-MF exposure, without considering other factors related to magnetic field generation. However, there is no reason to believe that this measurement error differed by outcome status. Thus, the true exposure would be the result of the predicted value plus a non-differential (Berkson-type) measurement error, which would increase uncertainty with wider confidence intervals but not introduce bias in the association estimates (Yland et al., 2022). When exposure was categorised to explore non-linear patterns, non-differential misclassification between adjacent categories may have biased the estimates toward one another (Lash et al., 2021). This could explain the higher risks observed for intermediate exposure categories and the absence of a consistent higher risk for the $\geq 0.3 \mu\text{T}$ (or $\geq 0.4 \mu\text{T}$) category. The magnitude of bias depends on the proportion of misclassified individuals (Yland et al., 2022). Because few individuals were exposed to high levels, estimates for low exposure categories are likely correct, whereas estimates for the highest category may underestimate the true association (Birkett, 1992). Lastly, we did not account for occupational exposure to ELF-MF, which may be an important predictor of the outcomes. However, because the relationship between occupational and residential ELF-MF exposure is not well characterised, it is unclear how this might have influenced the observed associations.

We relied on mortality data to assess the risk of neurodegenerative diseases, so outcome misclassification is another potential limitation of this study. It is well known that dementia and Parkinson's disease are often underreported on death certificates (Ganguli & Rodriguez, 1999; Romero et al., 2014), while ALS and multiple sclerosis are expected to be well documented (Horrocks et al., 2017). Underreporting of dementia mortality could, in principle, be differential if it is related to socioeconomic position, since individuals with higher socioeconomic position are more likely to be diagnosed with dementia (Holm et al., 2022). Because socioeconomic position may also be associated with ELF-MF exposure, with wealthier individuals tending to be less exposed (Schüz et al., 2000), underreporting would likely be more common among those with higher exposure. This would bias the estimates towards the null. Including socioeconomic position and education level in our models did not materially change the results, therefore any remaining differential outcome misclassification is likely to be limited.

Residual confounding by socioeconomic position, lifestyle factors, family history, or other unmeasured environmental exposures can never be fully ruled out. However, analyses using negative control outcomes did not show consistent associations, so substantial residual confounding by main lifestyle factors like alcohol consumption or smoking is unlikely. While confounding by another environmental factor remains possible, the E-values indicate that a confounder would need to have at least moderate to strong associations with both exposure and outcome to fully explain the observed associations. Such strong correlations are rare

in environmental epidemiology, making it unlikely that unmeasured environmental factors entirely explain the results.

5. Conclusion

Our study supports epidemiological evidence linking residential ELF-MF exposure to dementia risk in the general population, while no associations were found for other neurodegenerative diseases outcomes. The current lack of established biological mechanisms supporting our findings leaves the likelihood of a true causal relationship uncertain. Since high ELF-MF exposure from HVPL or railway lines is rare, population attributable fraction of Alzheimer's disease cases would be 1.01% for HVPL exposure and 0.43% for railway lines exposure, assuming the observed associations were causal.

Ethics declaration

The use of the SNC data for this project was approved by the Ethics Commission of Northwest and Central Switzerland (No. 2024-01728).

CRediT authorship contribution statement

Nekane Sandoval-Diez: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Nicolas Loizeau:** Writing – review & editing, Validation. **Anke Huss:** Writing – review & editing, Validation, Supervision, Methodology. **Martin Rössli:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Danielle Vienneau:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envint.2026.110145>.

Data availability

The authors do not have permission to share data.

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